

*Title : will be set by the publisher*  
*Editors : will be set by the publisher*  
*EAS Publications Series, Vol. ?, 2011*

# ASTROPHYSICAL CONSTRAINTS ON DARK MATTER

Charling Tao<sup>1</sup>

**Abstract.** Astrophysics gives evidence for the existence of Dark Matter and puts constraints on its nature. The Cold Dark Matter model has become "standard" cosmology combined with a cosmological constant. There are indications that "Cold" Dark Matter could be "warmer" than initially discussed. This paper reviews the main information on the Cold/Warm nature of Dark Matter.

## 1 Introduction

Warm Dark Matter (WDM) has become a hot topic and the debate is not settled. The Meudon Workshop 2011 was running in parallel to our CYGNUS Directional Direct Detection workshop followed in July by the 2011 Cosmology Colloque in Paris. Presentations from those two workshops are available online.

Due to the restricted number of pages, I skip the review on the astrophysical evidence for the existence of Dark Matter(DM). At all scales (galaxy, cluster and Universe) there are observations which point to the existence of a large quantity of DM. A small proportion of dark (ie, non luminous) matter may be baryonic: astronomical bodies, such as black holes, massive compact halo objects, or cold molecular hydrogen, ... DM, however, is currently defined in cosmological parameters fits, as non-baryonic and cold. Candidates include neutrinos, and other hypothetical entities such as axions, or supersymmetry particles, ...

Non-baryonic DM is classified as Hot Dark Matter (HDM), Warm Dark Matter (WDM), or Cold Dark Matter (CDM), depending on the velocity of the particles at decoupling. In the CDM hypothesis, the DM particles are massive and have small velocity. The most studied candidate is the supersymmetric neutralino of the MSSM (Minimal Supersymmetric Standard Model).

Hot DM particles (eg light neutrinos) would have velocities close to the speed of light. The DM velocity has consequence on the large scale structure (LSS) for-

---

<sup>1</sup> Centre de Physique des Particules de Marseille, IN2P3/CNRS and Université Aix-Marseille, Marseille, France  
 Tsinghua Center for Astrophysics, Tsinghua University, Beijing, China

mation. The CDM model yields "bottom-up" hierarchical formation of structures in the universe while HDM would induce preferentially "top-down" formation.

In the nineties, the development of N-body simulations of large scale structures (LSS) led to a preference for CDM models over HDM.

## 2 N-body simulations of LSS

S. von Hoerner (1960, 1963) pioneered the work on N-body simulations in the early sixties. Many simulations use only CDM, and thus include only the gravitational force. Incorporating baryons into the simulations dramatically increases their complexity and in the past, radical simplifications of the underlying physics was made. Only in the last decade have simulations tried to understand processes that occur during galaxy formation.

N-body simulations of cosmological structures with CDM have shown that the radial profiles of the mass density and velocity dispersion of DM haloes follow rather simple universal functional forms that are largely independent of halo properties such as mass, environment, and formation history. For the density profile, there have been many discussions about the value of the logarithmic slope of its central cusp, whether it is -1 (as for example in Hernquist (1990); Navarro et al. (1997)) or -1.5 as in Moore et al. (1998).

Results from more recent N-body simulations suggest actually a lack of a definite inner slope: the density profile of the now better resolved DM haloes continues to flatten with decreasing radius (e.g., Navarro et al. 2004; Merritt et al. 2005, 2006; Graham et al. 2006). Functional forms such as the Einasto (1969) or the Prugniel and Simien (1997) profiles, motivated by the Sersic profile for the surface brightness of galaxies (Sersic 1968) provide a more accurate fit to the more recent simulations.

Another parameter that has been used is the radial profile of the pseudo-phase-space density,  $\rho/\sigma^3$ , where  $\sigma$  is either the total velocity dispersion or the velocity dispersion in the radial direction. It seems well approximated by a power-law (e.g., Taylor and Navarro 2001; Ascasibar et al. 2004; Dehnen and McLaughlin 2005; Hoffman et al. 2007, Stadel et al. 2009, ...).

## 3 Comparison of N-body simulations with observations

At the end of the millenium, precision in N-body simulations of DM structures have shown some problems with a pure CDM model at small scales: the predicted number of galactic satellites was not observed (cf. eg, Klypin et al., 1999) and a cusp/core controversy in galactic centers developed. This has led some to conjecture WDM to explain the discrepancy. However, new observed faint galactic satellites and other explanations for the observed galactic cores could allow the CDM model to survive. In the mean time, the size of mini-voids in the local Universe and HI velocity functions and widths measurements have increased the importance of the so-called "overabundance problem" in pure  $\Lambda$ CDM simulations. But the controversy is still on...

### 3.1 Galaxy core profiles

Observations of rotations curves favour Burkert (1995) core profiles over the cusp profiles (cf eg., Donato et al. (2009), or Gentile et al.(2007)) from  $\Lambda$ CDM N-body simulations (eg., Navarro, Frenk and White (NFW 1996), or even Einasto form (1969)).

It has been shown (eg, Mashchenko, Couchman, and Wadsley, 2006) that stellar feedback can solve this difference by removing cusps. The numerical simulations with random bulk motions of gas (driven for example by supernovae explosions from star-forming galaxies) can flatten the central dark matter cusp on relatively short timescales ( $\sim 108$  years). Once removed, the cusp cannot be reintroduced during the subsequent mergers involved in the build-up of larger galaxies. As a consequence, in the present Universe both small and large galaxies would have flat dark matter core density profiles, in agreement with observations.

Romano-Diaz et al. (2008) proposed that baryons also can erase DM Cusps in Cosmological Galactic Halos. They find a different evolution between the Pure DM (PDM) and Baryon+DM(BDM) models within the inner few 10 kpc region. The PDM model forms a  $R^{-1}$  cusp as expected, while the DM in the BDM model forms a larger isothermal  $R^{-2}$  cusp instead. The isothermal cusp is stable until  $z \sim 1$  when it gradually levels off. This leveling proceeds from inside out and the final density slope is shallower than -1 within the central 3 kpc (i.e., expected size of the  $R^{-1}$  cusp), tending to a flat core within  $\sim 2$  kpc. This effect cannot be explained by a finite resolution of the code, neither is it related to the energy feedback from stellar evolution or angular momentum transfer from the bar. Instead it can be associated with the action of DM+baryon subhalos heating up the cusp region via dynamical friction and forcing the DM in the cusp to flow out and to cool down.

### 3.2 Number of galactic satellites

The recent discovery of many new DM dominated satellites of the Milky Way in the Sloan Digital Sky Survey (eg Belokurov, et al., 2010) has reduced the importance of the missing satellite issue.

Maccio and Fontanot (2010) and Polisensky and Ricotti(2011) have given lower limits of a few keV to DM particle mass from the number of Milky Way satellites, since the number of satellites predicted decreases with decreasing mass of the DM particle. Assuming that the number of satellites exceeds or equals the number of observed satellites of the Milky Way, Polisensky and Ricotti derive a lower limit on the DM particle mass of 13.3 keV (95%CL) for a sterile neutrino produced by the Dodelson and Widrow mechanism, 8.9 keV for the Shi and Fuller mechanism, 3.0 keV for the Higgs decay mechanism, and 2.3 keV for a thermal DM particle.

These lower limits are comparable to constraints on WDM mass from Lyman- $\alpha$  forest modeling (Narayanan et al. 2000; Viel et al. 2005,2008; Boyarsky et al. 2009a), high  $z$  quasar luminosity functions (Song and Lee 2009), X-ray observations of the unresolved cosmic X-ray background, DM halos from dwarf galaxy to cluster scales, (cf. eg. Boyanovsky, de Vega, Sanchez 2008 ; de Vega and Sanchez 2009

for reviews).

### 3.3 *HI velocity functions*

In their very recent paper, Papastergis, Martin, Giovanelli and Haynes (2011) present results from 40% of the ongoing wide-area, extragalactic HI-line, Arecibo Legacy Fast ALFA (ALFALFA) survey. They measure the space density of HI-bearing galaxies as a function of their observed velocity width (uncorrected for inclination) down to velocities of 20 km/s and confirm previous indications (Zavala et al., 2009; Gottloeber, Hoffmann and Yepes, 2009; Trujillo-Gomez et al., 2010) of a substantial discrepancy at low widths between the observed distribution and the  $\Lambda$ CDM simulations.

There is an overabundance of model galaxies by a factor of  $\sim 10$  compared to observed dwarf galaxies with circular velocity  $V_{circ} < 50$  km/s. This is a serious problem for the  $\Lambda$ CDM model: galaxies with these small circular velocities cannot be affected much by normal physical processes (e.g., supernovae feedback or reionization of the Universe) proposed for the solution of the satellite problem at  $V_{circ} < 30$  km/s. The difference in abundance is a factor of about 8 at  $v = 50$  km/s (which corresponds to the resolution limit of the Zavala et al.(2009) simulation, and implies a difference of a factor of  $\sim 100$  when extrapolated to the ALFALFA low-width limit ( $v = 20$  km/s).

Papastergis, Martin, Giovanelli and Haynes (2011) also examine several solutions to the discrepancy: (i) a 1 keV WDM scenario and (ii) HI disks in low mass galaxies are usually not extended enough to probe the full amplitude of the galactic rotation curve. In this latter case, they infer a relationship between the measured HI rotational velocity of a galaxy and the mass of its host CDM halo, which should be checked to provide an important test of the validity of the established CDM model.

### 3.4 *Mini-voids size*

Tikhonov and Klypin (2010) have studied the luminosity function, peculiar velocities and sizes of voids in the Local Volume within the distance 4-8 Mpc. The predictions of the standard cosmological  $\Lambda$ CDM model give a factor of 10 more dwarf haloes as compared with the observed number of dwarf galaxies. The theoretical void function matches the observations remarkably well only for haloes with circular velocities  $V_c$  larger than 40-45 km/s. For haloes with circular velocities  $< 35$  km/s, there are too many small haloes in the  $\Lambda$ CDM model resulting in voids being too small, as compared with observations. The problem is that many of the observed dwarf galaxies have HI rotational velocities below 25 km/s that strictly contradicts the  $\Lambda$ CDM predictions. This is related to the "overabundance problem", and could be solved by the same assumptions about keV WDM or HI disks in low mass galaxies.

### 3.5 Conclusion on the problems with $\Lambda$ CDM?

$\Lambda$ CDM N-body simulations are fitting impressively well a wealth of data. To-date discrepancies concern the "overabundance problem", which could, however, be due to the inability of HI to trace the maximum halo rotational velocity of low-mass systems. So CDM is not dead yet!

The effects of WDM compared to CDM on the structure formation is to remove power from small scales, due to the large thermal velocities of the particles. Future lensing projects like EUCLID, can provide measurements of a WDM mass for masses  $< 2.5$  keV, since the cosmic shear power spectra depends on the DM mass (Markovic et al. 2011), and departure from the CDM power spectra is not sensitive above roughly 2.5 keV. In order to fully exploit future observations, models should be able to predict the non-linear matter power spectrum at the level of 1 per cent or better for scales corresponding to comoving wavenumbers  $0.1 < k < 10$  h Mpc $^{-1}$ . However baryonic and other astrophysics effects (stellar, supernovae, AGN feedbacks, ... ) can have large impacts on the measured power spectrum at small scales. this has been verified by different groups of N-body simulations: eg., Gottloeber et al., (2010), CLUES project; Guillet, Teyssier and Colombi (2010), MareNostrum; Viel et al. (2011), Gadget-2; van Daalen et al.(2011), OWLS, ...

Comparison of N-body simulations of LSS with measurements can thus exclude pure HDM solutions and set lower limits on the DM mass to be about a few keV. Above a few keV, there is no current clues on how to separate WDM from CDM.

## 4 Importance of Baryonic physics in N-body simulations

The importance of baryonic physics in N-body simulations and weak lensing has been ignored till 2004. White (2004) and Zhan and Knox (2004) calculated the effects of cooling and intra-cluster gas on the lensing power spectrum. These components have each an effect of a few percent on the lensing power spectrum at  $l$  around 3000, but with opposite signs. Jing et al. (2006) were the first to include in a N-body gas simulation the physical processes of radiative cooling and star formation, supernova feedback, outflows by galactic winds, and a sub-resolution multiphase model for the interstellar medium.

More recently, Sales et al.(2010) studied the properties of simulated high-redshift galaxies using cosmological N-body gas dynamical runs from the Over-Whelmingly Large Simulations (OWLS) project. The different feedback models they use result in large variations in the abundance and structural properties of bright galaxies at  $z=2$ . The OWLS simulations have also been used by van Daalen, Schaye, Booth, and Dalla Vecchia (2011) to study the distribution of power over different mass components, the back-reaction of the baryons on the CDM and the evolution of the dominant effects on the matter power spectrum. Single baryonic processes are capable of changing the power spectrum by up to several tens of per cent. The simulation that includes AGN feedback, predicts a decrease in power relative to a dark matter only simulation ranging, at  $z=0$ , from 1 per cent at  $k \sim 0.3$  h Mpc $^{-1}$  to 10 per cent at  $k \sim 1$  h Mpc $^{-1}$  and to 30 per cent at  $k \sim 10$

$h \text{ Mpc}^{-1}$ . They confirm that baryons, and particularly AGN feedback, cannot be ignored in theoretical power spectra for  $k > 0.3 h \text{ Mpc}^{-1}$ . It is necessary to improve our understanding of feedback processes in galaxy formation.

## 5 Candidate DM: the sterile neutrino

### 5.1 *The need for sterile neutrinos*

In the early times of the Standard Model of particles, neutrinos were thought to be massless and different lepton numbers were believed to be conserved. This was a reason for not introducing righthanded neutrinos. However, the observation of neutrino oscillations in experiments with solar, atmospheric, accelerator and reactor neutrinos requires the addition of new particles to the Standard Model. Thus the interest in "sterile" neutrinos which are right-handed, and have very weak (if any) interactions, besides gravity... Sterile neutrino can be cold or warm DM depending on the models and parameters. Shaposhnikov, Boyarsky, and their collaborators presented many different models of sterile neutrinos. A relatively new review of astrophysical and cosmological constraints on some models can be found in Boyarsky, Ruchayskiy and Shaposhnikov (2009). The conclusion is that "Realistic Sterile Neutrino Dark Matter with KeV Mass does not Contradict Cosmological Bounds" (Boyarsky, Lesgourgues, Ruchayskiy, and Viel, 2009), in agreement with the many astrophysical and laboratory constraints on WDM mass (and neutrino mixing angles), which were first thoroughly investigated by Abazajian et al.(2001,2006,...) with the then existing data.

### 5.2 *Has a sterile neutrino of 5 KeV been found?*

Since 2006, several groups have searched for decaying DM (cf eg, the many papers of Boyarsky et al., 2006 and after) and set constraints on sterile neutrino model parameters. Loewenstein and Kusenko (2010) report the presence of a narrow emission feature with energy  $2.51 \pm 0.07(0.11) \text{ keV}$  and flux  $[3.53 \pm 1.95(2.77)] 10^{-6} \text{ photons cm}^{-2} \text{ s}^{-1}$  at 68% (90%) confidence in the Chandra X-ray Observatory spectrum of the ultra-faint dwarf spheroidal galaxy Willman 1. Interpreting this signal as an emission line from sterile neutrino radiative decay, the feature is consistent with a sterile neutrino mass of  $5.0 \pm 0.2 \text{ keV}$ . But this signal is too weak and would need confirmation before a claim of discovery can be made.

## 6 Conclusion

Since Cygnus is a Directional Direct Detection workshop, news about a keV DM candidate discovery can be a bit unsettling. It is important to keep an open eye on currently discussed candidates since it can have consequences on our projects. If an Universe with only HDM can be excluded, it is not possible to-date to rule out neither CDM nor WDM. There are still many questions: Can we trust present N-body simulations? They are impressive but halos from the simulations are not

galaxies. Are all baryonic and other astrophysics effects well taken into account? The Wilman1 feature is not convincing, so whether DM is Cold or Warm and in the keV range is still not settled. Furthermore, even if WDM in the keV range existed, it is not excluded that more massive CDM would be also present. Finally, there are (many?) other particle candidates than keV sterile neutrinos. Lin et al. (2001) have, for example, proposed the non-thermally produced decaying DM, which could reconcile CDM and WDM. Some phenomenology has been presented by Bi et al. (2010). Considering the long timescales of Direct DM Detection efforts, I imagine non-thermally produced decaying DM could be an alternative, welcome by this community...

## 7 Acknowledgements:

Many thanks to Frederic Mayet, without whom I would not have reviewed the subject in Aussois. His gentle pressure has given birth to this written version... I am also grateful to Daniel Santos who has kept, for so many years, the steady direction of TPCs for DM, and has continuously shared with me the progress of his team. The workshop has allowed me to meet the new generation of enthusiastic DM research people and I enjoyed the Aussois environment. The content of this talk has been enriched by discussions with Zhang XinMin, Qin Bo, Shan HuanYuan, Bi XiaoJun and Zhan Hu.

## References

- [http://www.chalonge.obspm.fr/CIAS\\_Meudon2011.html](http://www.chalonge.obspm.fr/CIAS_Meudon2011.html),  
<http://www.chalonge.obspm.fr/colloque2011.html>  
 Abazajian, K., Fuller, G. M., Patel, M. 2001, Physical Review D, 64, 023501  
 Abazajian, K. 2006, Physical Review D, 73, 063513  
 Ascasibar Y., Yepes G., Gottlober S., Muller V., 2004, MNRAS, 352, 1109  
 Belokurov, V. et al. 2010, Ap.J. Letters, 712, L103-L106.  
 Bi, X.J. et al. 2009, Physical Review D, 80, 103502  
 Boyanovsky, de Vega, Sanchez N. 2008, Phys. Rev. D 77, 043518  
 Boyarsky, A. et al. 2006, PRL 97:261302  
 Boyarsky, A., Lesgourgues, J., Ruchayskiy, O., Viel, M. 2009, JCAP 012  
 Boyarsky, A.; Lesgourgues, J.; Ruchayskiy, O., Viel, M. 2009, PRL, 102, 201304  
 Boyarsky, A., Ruchayskiy, O., Shaposhnikov, M. 2009, Annual Review of Nuclear and Particle Science, 59, 191-214  
 Boyarsky, A. et al. 2010, MNRAS, 407, 1188-1202.  
 Bertschinger, E. 1998, Annual Review of Astronomy and Astrophysics 36  
 Burkert, A. 1995 Astrophys. J. 447, L25 [arXiv:astro-ph/9504041].  
 Clowe, D; et al. 2006, Ap.J. Letters 648 (2): L109L113, arXiv:astro-ph/0608407.  
 van Daalen, M. P. et al. 2011, MNRAS, 415, 3649-3665.  
 Dehnen W. and McLaughlin D. E., 2005, MNRAS, 363, 1057  
 Donato, F. et al., 2009, MNRAS, 397, 1169

- De Vega, Sanchez N. 2010, MNRAS 404, 885894
- Einasto J., 1969, *Astrofizika*, 5, 137
- Gentile, G. Salucci, P. Klein, U. Granato, G., 2007, MNRAS, 375, 199
- Gottloeber, Hoffman Y., Yepes 2010, in "High Performance Computing in Science and Engineering, Garching/Munich", Springer-Verlag, arXiv:1005.2687
- Graham, A. W., et al. 2006, AJ, 132, 2701
- Guillet, T., Teyssier, R., Colombi, S. 2010, MNRAS, 405, 525-534.
- Hernquist, L., 1990, ApJ, 356, 359
- von Hoerner, S. 1960, *Zeitschrift für Astrophysik* 50: 184.
- von Hoerner, S. 1963, *Zeitschrift für Astrophysik* 57: 47.
- Hoffman Y., Romano-Diaz E., Shlosman I., Heller C., 2007, ApJ, 671, 1108
- Kaplinghat M. 2005, Phys.Rev.D72:063510
- Klypin, A. A. et al. 1999, *Astrophys. J.* 522, 82 [arXiv:astro-ph/9901240].
- Lin, W. B., Huang, D. H., Zhang, X., Brandenberger, R. 2001, PRL, 86, 954-957
- Loewenstein, M., Kusenkov, A. 2010, ApJ, 714, 652-662
- Maccio, A. V. and Fontanot, F. 2010, MNRAS Letters, 404, L16-L20.
- Ma, C.P., Chang, P., and Zhang, J. 2009, eprint arXiv:0907.3144
- Mashchenko, S., Couchman, H. M. P., Wadsley, J. 2006, *Nature*, 442, 539-542.
- Markovic, K., Bridle, S. Slosar, A. Weller, J. 2011, JCAP, 022 .
- Merritt, D., Navarro, J. F., Ludlow, A., Jenkins, A. 2005, ApJL, 624, L85
- Merritt, D et al. 2006, ApJ, 132, 2685
- Moore B. 1994, *Nature* 370, 629.
- Moore, B., et al. 1998, Ap. J. 499, L5 (1998) [arXiv:astro-ph/9709051].
- Narayanan, V. K.; Spergel, D.N.; Dav, R.; Ma, C.P. 2001, ApJ, 543, L103-L106.
- Navarro, J. F., et al., 2004, MNRAS, 349, 1039
- Navarro J. F., Frenk C. S., White S. D. M., 1997, ApJ, 490, 493
- Papastergis E., Martin A., Giovanelli R., Haynes M. 2011, arXiv:1106.0710
- Polisensky, E., Ricotti, M 2011, *Physical Review D*, 83, 043506
- Prugniel P. and Simien F. 1997, A&A, 321, 111
- Romano-Diaz, E., Shlosman, I., Hoffman, Y., Heller, C. 2008, Ap. J. 685, L105-L108.
- Sales, L. V. et al. 2010, MNRAS, 409, 1541-1556
- Stadel, J. et al. 2009, MNRAS, 398, L21-L25.
- Semboloni, E. et al. 2011, eprint arXiv:1105.1075
- Sersic J. L., 1968, *Atlas de galaxies australes*
- Song, H., Lee, J. 2009, ApJL, 703, L14-L17.
- Smith, R. E. and Markovic, K. 2011, eprint arXiv:1103.2134
- Taylor J. E., Navarro J. F., 2001, ApJ, 563, 483
- Teyssier, R. et al., 2011, MNRAS, 414, 195-208.
- Tikhonov A., Klypin A. 2010, MNRAS, 395, 1915-1924.
- Viel, M., 2005, IAU Colloquium Proceedings of the International Astronomical Union 199, "Probing Galaxies through Quasar Absorption Lines" Cambridge University Press , 255-260,
- Viel, M., et al. 2008, PRL, 100, 041304
- Viel, M., Markovic, K. Baldi, M. Weller, J. 2011, eprint arXiv:1107.4094
- Zavala, J. et al. 2009, ApJ, 700, 1779